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Micromachined Louver Arrays for Spacecraft Thermal Control Radiators

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Small spacecraft, including nano and picosats, as they are envisioned for future missions will require adaptive thermal control systems due to their small power and mass budgets. One of the proposed technologies is variable emissivity coatings for spacecraft radiators. Three systems have been chosen as demonstration technologies on NASA's New Millennium Program ST5 spacecraft, including micro-machined louver arrays. These gold coated structures have micrometer scale features and expose a high emissivity radiator substrate to space in the open state. They can be operated independently and allow digital control of the effective emissivity. This paper discusses the latest micromachined louver prototype for ST5 spacecraft and its integration into the thermal control system

Introduction

Present and future space missions with small satellites require low power, adaptive thermal control technologies due to the increased thermal fluctuations in these satellites due to their small thermal mass. In an increasing number of satellites, optical alignment and calibration require a strict temperature control. Traditionally, the thermal design is part of the spacecraft layout that is determined by all subsystems and instruments. Heat load levels and their location on the spacecraft, equipment temperature tolerances, available power for heaters, view to space, and other such factors are critical to the design process. Smaller spacecraft with much shorter design cycles and fewer resources including heater power, volume, and surface, require an active approach. Traditionally, active thermal control is applied using heaters, variable conductance heat pipes, and tranditional mechanical louvers to control the radiator effective emissivity.[1] For small satellites, all theses approaches could require more mass or power than is available. A new, more flexible approaches is a radiator coating with a variable infrared emissivity that can be actively adjusted in response to variations in the thermal load and environmental conditions. An elegant solution for small spacecraft involves the use of miniature louver arrays on the radiator to control its emissivity.[2,3] These louvers are surface micromachined from polysilicon, with each single louver in the order of 300 μm x 500 μm. There will be on the order of 400 louvers per square cm, which can be opened and closed in arrays of 8 to 16 by electrostatic linear motors. The louvers are gold coated, and in the open state, expose a high emissivity substrate to space. It is expected that the louvers will allow linear digital control of the effective emissivity between approximately 0.1 and 0.9 with between 8 and 16 bit resolution. The radiator can thus be adapted to a very broad range of thermal requirements during flight, which greatly increases a thermal engineer's design flexibility.

The feasibility of the louver concept has been demonstrated through several generations of prototype micro-machined louver arrays.[2,3] This paper will discuss results of the latest prototypes, which were fabricated with Sandia National Laboratories' SUMMiT V process.

Space Technology 5

The Space Technology 5 (ST5) mission is the fourth space mission in NASA's New Millennium Program. The mission will attempt to fly three miniature spacecraft, each 42 centimeters (17 inches) across, 20 centimeters (8 inches) high, and with a weight of 21.5 kilograms (47 pounds) in a Molniya

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orbit with 185 km perigee and 35,786 km apogee altitudes. The mission is planned for launch in 2003 as a secondary payload on an expendable launch vehicle and is budgeted at $28 million.

The mission objective is to test methods for operating a constellation of spacecraft as a single system and to test and flight-validate eight innovative new technologies in the harsh space environment of Earth's magnetosphere. One of these technologies is variable emissivity coatings for active thermal control. For the science mission, the spacecraft will carry energetic particle detectors and magnetometers for making measurements of particles and electrical currents generated during magnetospheric storms and substorms.

<u>Thermal Control System on ST5</u>

The MEMS louvers are one of the three variable emissvity coating (VEC) technologies on ST5 to be used for thermal control. The two other technologies to be tested are electrophoretic and electrochromic coatings. Each of these technologies will cover a 90 cm^2 radiator, with two technologies per spaceraft. One technology will be flown on the top surface and the other on the bottom. The technology objective is to validate the variable emissivity coatings as functional radiator while mitigating risk due to failure.

The exact orbit depends largely on the launch opportunity, and the spacecraft thermal design has to be prepared for the extreme cases. This is precisely one of the applications of the VECs, to generate a thermal design that works over a broader range of conditions, allowing for greater flexibility in the spacecraft design. Extreme cases for the ST5 orbit include a 1.88 hour eclipse at apogee in one case, and full sun in the another case.

In order to maintain the spacecraft temperature within the operational limits of -20 °C to +40 °C, the solar arrays on the side of the spacecraft are conductively isolated but radiatively coupled to the spacecraft. This limits the temperature variation caused by the VEC to less than 2K, which is considered to be small to validate the technology. Therefore, the radiators have been isolated from the spacecraft, and coupled with a conductance of 0.1 W/K between the VEC and the deck. Figure 1 shows the temperature as a function of time for an cold case orbit, which includes a 2.1 hr eclipse, with the louvers in the open and closed position as well as the temperatures on one of the fixed radiators. Temperatures vary between –12 and 4 °C. in the closed case, and –30 to –15 °C in the open case. The variable emissivity system will be controlled within these two limits, with the set temperature for this orbit set at a temperature within these extreme cases.

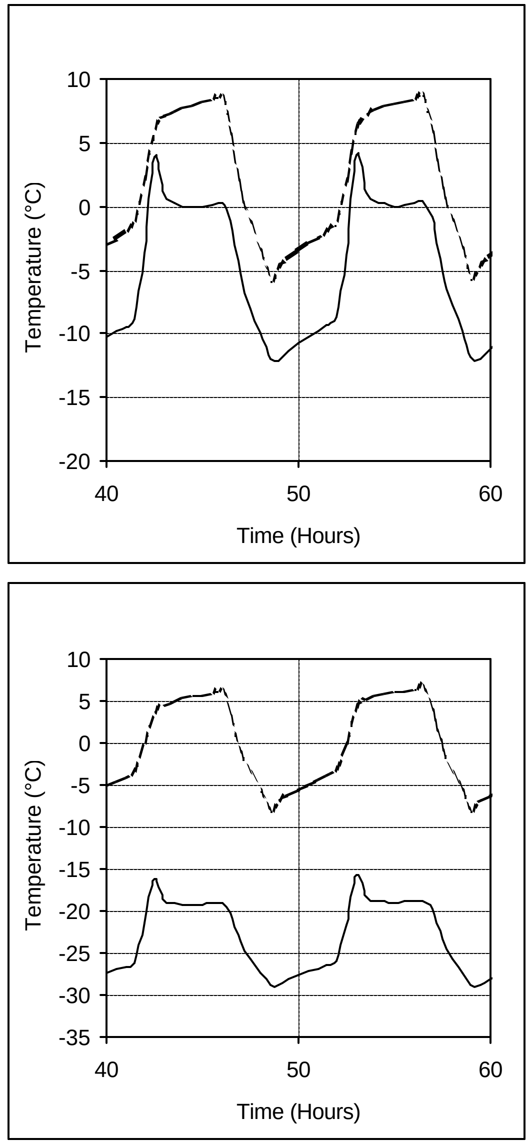

Figure 1: Temperature of a VEC (solid) and a fixed (dashed) radiator as a function of time for an cold case orbit with the louvers in the close (top) and open (bottom) position.

The variable emissivity surface, in the case of failure in one of the two positions, will never exceed the survival temperatures given for the spacecraft.

<u>MEMS Louver Concept</u>

MEMS louvers are similar in design to traditional macroscopic louvers in that they can be opened or closed to expose an underlying high emissivity radiator. Their small size, a few hundreds of micrometers, allows for a different mode of operation. The devices are attached to the radiator surface and do not add substantial weight or bulk

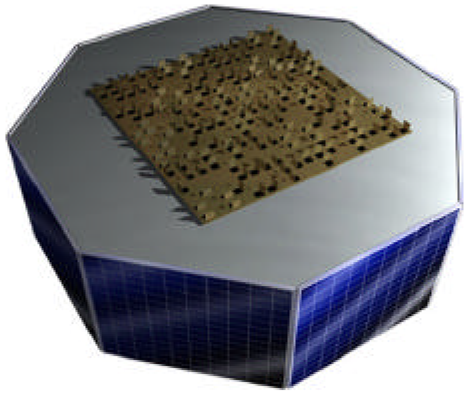

Figure 2: Artist's perception of a partially closed MEMS variable emissivity radiator

to the spacecraft. The large number of louvers, which can ideally be actuated independently, also allows for control of the number of open and closed louvers and does not require any intermediate position. An artist's rendition of such an louver array is shown in Fig. 2. The louvers open in equal numbers in multiple directions, which will reduce the solar absorption. The small size of the louvers, only a few hundred microns, reduces the reflection of sunlight onto the radiator. Three different MEMS designs have been investigated and fabricated. These designs are depicted schematically in Fig. 3. The simplest design is a louver that can be opened to a vertical position to expose an area of the high emissivity substrate to space. In the second design, multiple levels of sliders move across each other. In this case, the total area, which can be exposed, depends on the number, n, of layers available in the fabrication process and is about $(1-1/n)$ times the slider area. Advantages of this approach include the two-dimensional design, the linear variability of exposed area, and the sturdiness of the design. The third prototype mimics a bi-fold door. This design is more complicated than the other two since it uses more hinges, but we expect it to be more rugged than the single louvers while providing the same active area. Preliminary experience has shown that these devices are less likely to break during release and operation.

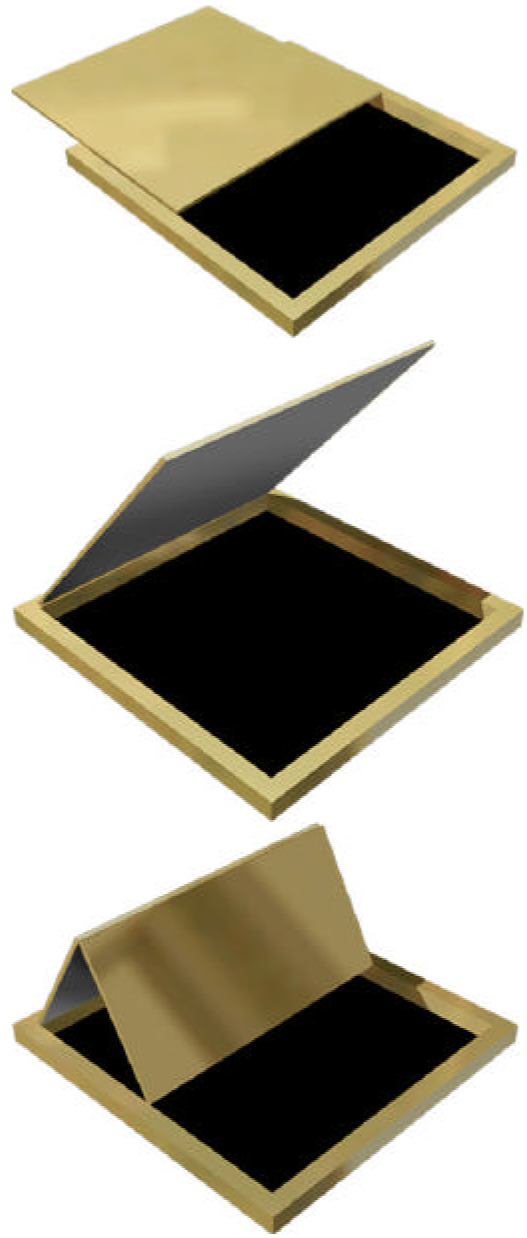

Figure 3: Schematic of the different MEMS concepts: Slider (Shutter), Louver, and Folder.

MUMPs Louver Arrays

For all three designs, MEMS prototypes have been designed at the Applied Physics Laboratory (APL), fabricated at the Cronos Foundry using their Multi-User MEMS Process (MUMPs), and subsequently released and tested at APL. The base material for the current devices is polysilicon and the exposed, top surface is coated with gold. The vapor deposited gold has an absorptivity of 0.3 in the visible and an emissivity of 0.02 in the infrared. To expose the high emissivity radiator, the silicon substrate under the louvers has been removed using deep reactive ion etching (DRIE). Emissivity measurements showed a change in effective emissivity from 0.5 to 0.88, with the offset of 0.5 given mainly by the uncoated support structures. A visible image of an 3 x 4 louver array with the substrate removed in the closed and partially open position is shown in Fig. 4. Where the louvers are open, the radiator can be seen through the etch holes. A point of concern for this generation of louvers was the actuation mechanism. While electrostatic comb drives fulfill all the requirements on force and low power consumption, the

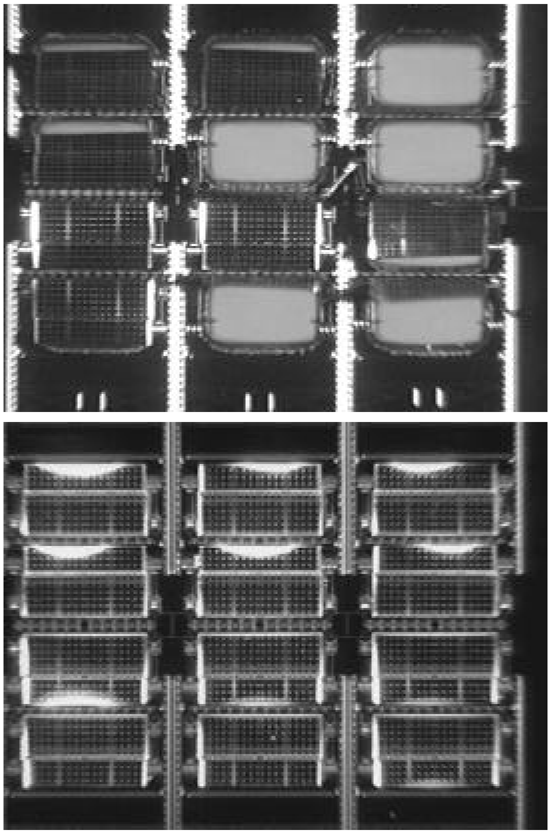

Figure 4: Optical image of louver array, with open louvers (top) and all louvers closed (bottom). The open louvers expose the background through the etched openings.

devices occupy a large surface area, which causes a large offset in the possible emissivity variation. In order to increase the force to area ratio of the motors, a 5-level surface machining technology was used for the next prototype system.

SUMMiT V Shutter Arrays

Sandia National Laboratories has developed a 5-level polysilicon surface machining process, Sandia Ultra-Planar Multi-Level MEMS Technology 5 (SUMMiT V), that offers significantly increased system complexity.[4] One result of this complexity is a new class of high force, low voltage actuation systems. Since the force obtainable from an electrostatic comb drive is roughly proportional to its area and the thickness, the thickness increase with the 5 layer process reduces the required area for the same force.[5] The SUMMiT V process consists of a 0.3 μm thick polysilicon electrical interconnect layer (poly0), and 4 mechanical levels polysilicon separated by a sacrificial polysilicon dioxide films (poly1 and poly2 are 1 μm and 1.5 μm thick, respectively, and separated by 0.5 μm silicon dioxide, poly 3 and 4 are 2.25 μm thick and separated by a 2 μm sacrificial layer). The sacrificial layers beneath poly3 and poly4 are planarized, which eliminates some of the processing artifacts of e.g. the MUMPs process due to the conformal film deposition, which propagates the topography to all successive layers.

One of the prototypes designed for the SUMMiT V process was a shutter array based on the use of an electrostatic comb drive. Figure 5 shows images with different magnification of the array and the comb drive, taken from a video of the devices in operation. The total array area is 5278μm x 2632μm, with each individual actuator area 225μm x 183μm and each group of six actuator elements and shutters 1767μm x 876μm. This particular actuator design has been found to be quite robust and reliable in its operation. It has a displacement of 6 μm and produces several hundreds of microNewtons of force, which is suitable for moving large arrays of shutter elements. The entire array, which covers a module area, will be gold-coated and will have a backside vias. The area is parsed into nine independently controllable areas which could be controlled in a open-closed binary manner or continuously using analog control over the range of opening. Each of the nine areas has six actuators associated with the shutter panels in that area. This design, including the dead space for the actuators, allows a variation of the effective emissivity of about 40%. Repeating the design on a six inch wafer will provide enough devices to cover the area required for the ST5 VEC radiator.

For the present prototype, the shutters are spring-loaded to remain in the closed position and require the voltage to be applied to expose the radiator. Since the current flow is below 1 μA, this will not result in high power consumption during operation and allows for simple control algorithms to be used. An advantage might be that a dynamically driven system, where no shutter is in the same position for extended times, might be less susceptible to become stuck, but is exposed to higher wear due to friction. Nevertheless, in order to reduce power for large area devices, a latching mechanism will be added to the next shutter prototype.

One advantages of the shutter design is its robustness and reliability, being directly coupled to the comb drive actuator without any hinge structures. The planar geometry will also remove light absorption for skimming incidence, as it is a problem for large louvers exposing structures to the skimming light when in the open position.

A disadvantage of this design is obviously the limitation to less than 50% emissivity change (not even considering the actuation). Even with another layer of shutters added (possible with the SUMMiT process), the theoretical limit for the emissivity variation is below

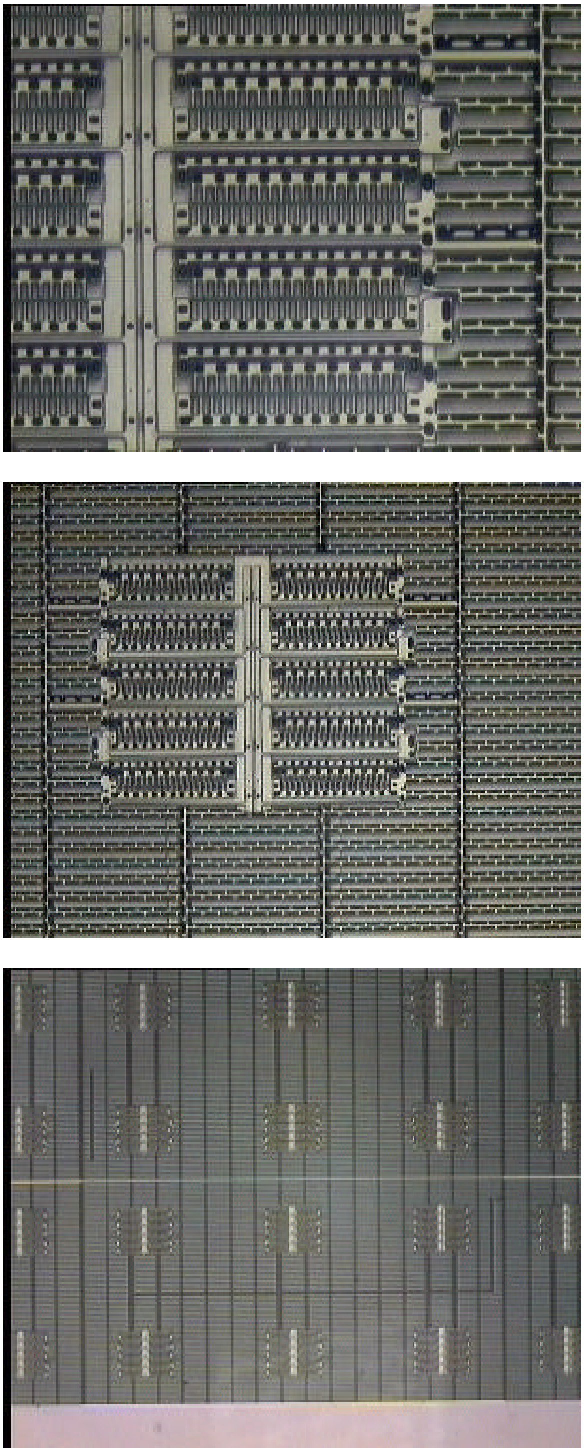

Figure 3: MEMS shutter array in different magnifications. The images are snapshots from videos showing the arrays in motion. The horizontal line in the bottom picture is the separation between two independently controlled areas, of which only one is switched.

66%. Another disadvantage is the large moving area, which could jam due dust particles or debris from the friction process. Many experiments will be performed during the space qualification process to estimate the lifetime of the devices under space conditions.

MEMS Reliability in Space

At present, there is very little knowledge about the reliability of moving MEMS structures subjected to launch and the harsh space environment. In addition, the effects of pre-launch storage must also be taken into consideration. A non-exhaustive list of the of MEMS reliability concerns includes: stiction, wear, fatigue, contamination, and radiation effects.[6]

Although stiction has not been observed in the prototype devices, the MEMS louvers are probably susceptible to this failure mechanism as a result of electrostatic interactions, capillary forces, or even localized cold welding.[7] These concerns can be addressed in several ways. For example, proper ground design should minimize the potential mechanical seizure due to electrostatic clamping. Excessive condensation of moisture, especially during pre-launch storage, can be mitigated through the use of hydrophobic coatings and out-gassing techniques. Furthermore, appropriate packaging could be employed to prevent the accumulation of water and other contaminants on critical surfaces of the devices during pre-launch conditions.

Relative humidity (RH) levels in excess of 70% have been associated with degraded mechanical performance attributed due to increasedstiction. However, elevated frictional wear between contacting parts has been observed in extremely low RH environments.[8] Due to the negligible RH of the intended operational environment, the possible degradation of the guides for the shutters over the device lifetime is an important issue. Minimum lifetimes will be on the order of 10,000 to 50,000 cycles depending on the control algorithms and the thermal conditions. Various coatings and design modifications to minimize friction are being considered.

Finally, in a space environment, the MEMS louvers will be subjected to high-energy irradiation. As a result, charge buildup in dielectric layers could occur which may lead to inconsistent or degraded operation of either the louvers or electrostatic actuators. To reduce the risk of failure, the shutter arrays and the comb drive actuators will be gold coated with proper ground (substrate) connection to prevent any charge built-up.

Conclusions

It has been shown in multiple models[3] that VEC technology offers significant advantages over current approaches for radiators in low UV environments. The heater power, mass, and cost savings that can be realized with these systems are potentially significant for many future spacecraft design applications. In addition, VEC coatings allow a more flexible thermal design, which is important for spacecraft such as ST5 that are launched as a secondary payload and the orbit parameters are not well defined known during the design period. The ST5 mission will demonstrate three VEC technologies and, if successful, provide validation for their use in future spacecraft. At this point, fully actuated prototypes of MEMS shutter arrays have been fabricated and will undergo critical reliability and space qualification testing before the fabrication of the 90 cm^2 radiator for ST5 will begins. Finally, the inclusion of the MEMS VEC technology on ST5 will provide important information about the performance and the reliability of actuated MEMS devices in space.

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